Comparative Study of the Energy Absorption Capacities of XPS and XPE Foam Filled Aluminium Square Tubes under Quasi-Static Axial Compression

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Abstract:*Quasi-static compression tests were performed on empty and foam filled Aluminium square tubes. Two different foam types: Extended Polystyrene (XPS) and Extended Polyethylene (XPE) were used to fill the empty tubes. In this paper experimental and numerical simulations were performed to investigate the effect of foam filling on crashworthiness parameters.*

Keywords: XPS, XPE, Specific Energy absorption, Crush Force efficiency

I. Introduction

The impact of transport vehicles is undesirable but occurs now and then. Hence, it is important to design the transport structures to withstand impacts and crashes. There is a continuous demand for the design of light weight structures which puts greater demands on the designer since more aspects of design become critical as the working stresses become closer to the ultimate strengths of the material. These light weight structures eventually improve fuel economy and emissions along with reduced cost.

A typical Load-displacement response during an impact of tubular structures shows an initial peak load which is usually much higher than the calculated mean load. Ideally the load must rise to a threshold value that will cause no harm to passengers and remain constant for the subsequent deformation (Faris Tarlochan 2014). The initial high peak load is caused by the formation of the first plastic fold. Depending on the specimen or component geometry, subsequent folds begin to form after or during the formation of the first fold. Each subsequent smaller peak represents one fold.

There are several parameters that are significant in any crash analysis. They include: Peak Load, Energy absorption, Crush Load efficiency (CFE), Specific Energy Absorption (SEA), and Mean Load (P_m). These are important parameters for comparing the effectiveness of the energy absorber.

Energy absorption is calculated as the area under the load-displacement curve during impact process and SAE is the energy absorbed per unit weight of the absorber

P_m and P_{max} are used to describe the characteristics of an absorber. The larger value of P_m corresponds to larger value of the energy absorbed and the goal of the design is to maximize it. On the other hand, there is a continuous attempt to decrease the value of P_{max}. Accordingly, CFE is defined (J. Marzbanrad 2014) as the ratio of the mean force to the initial peak force.

There have been ongoing attempts to increase the energy absorption capability of tubular structures. Methods such as frusta, Multi-corner columns, Sandwich plates, Honeycomb cells, Tube inversion and tube splitting have been investigated with this regard (Alghamdi 2001). Methods to reduce peak load by introducing Grooves (S.J. Hosseinipour 2003) and slots (Amir Radzi Ab. Ghani 2012) have been studied.

In last few decades, foam- filled tubes are given much attention in crashworthiness applications. Aluminium foam and Polyurethane foam have gained popularity due to their high specific strength, cost and ease of manufacturing. Foam-like lattices are often used for cushioning, packaging or to protect against impact, utilizing the long, flat plateau of their stress–strain curves (Ashby 2006). The increased number of lobes created by introducing foam filler causes the force level of the foam-filled tubes to be significantly higher than that of the combined effect of empty tube and foam separately (Hong-Wei Song 2005).

Many investigations have been carried out on tube structures filled with Polyurethane foams (K. A. Kamarudin 2008), (Nirut Onsalung 2010), (REID 1993).

In this paper, the energy absorption capacities of Polystyrene and Polyethylene foams are studied.

II. Specimen Preparation

6063-T6 Aluminium alloy tubes are available in lengths of 12 feet for commercial use. The square tubes of dimension 2inch X 2inch and of thickness 3 mm were selected for the study. Nine test samples were cut from these tubes and machined to a length of 150 mm each. Out of these nine samples, three were filled with XPS foam, three with XPE foam and the remaining three were left empty. The XPS and XPE foams are available in the form of 50 mm thick sheets and these were cut and inserted into the tubes. Each foam is of density 46 kg/m^3.

The dimensions were measured using a digital Vernier calliper of 0.01 mm least count. The weights of each sample are measured using digital weighing scale PRITECH (Model No, KL-Z-030) with least count of 0.1 g. The lateral dimension of the tube varied from 51.09 mm to 52.10 mm. However, the thickness of the tube varied from 3.02 mm to 3.24 mm and height of the specimen varied from 149.5 mm to 151.44 mm over the entire specimen

samples. All dimensions are measured at room temperature. Details of the test specimen are shown in the Table 1

Table 1: Specimen details

Ref No	Foam	Tube dimensions (mm)				Tube weight (g)	
		W	B	t	H	Empty	Filled
EE5A	-	51.09	51.74	3.24	151.44	243.1	-
EE5B	-	51.87	52.00	3.11	150.12	241.0	-
EE5C	-	51.99	52.10	3.10	150.76	242.0	-
EF4G	XPS	52.04	51.96	3.23	150.41	241.1	255.3
EF4H	XPS	51.95	51.86	3.10	152.02	243.4	257.8
EF4J	XPS	51.61	51.69	3.23	149.50	240.8	255.0
EF4K	XPE	52.10	51.78	3.18	150.21	239.8	254.1
EF4L	XPE	51.71	51.99	3.02	150.63	241.6	256.5
EF4M	XPE	51.72	51.96	3.04	150.62	241.6	255.8

III. Material Properties

Standard tensile test specimen was machined out from the tube made out of Aluminium 6063-T6. The test specimen was machined from the same tube that was subjected to compression-load test in the present experimental study.

Tensile test was conducted on TUE-C-1000 tensile test machine as per Test reference IS 1608-2005. The extensometer of 50 mm gauge length was used to obtain stress-strain diagram for the tensile test specimen.

The Figure 1 shows the stress-strain curve for the material of the tube. The Aluminium alloy shows tensile strength of 148.2 MPa, while its yield strength is 116.8 MPa. It showed elongation of about 12.64%. The young's modulus and the tangent modulus were then estimated to be respectively 60 GPa and 550 MPa.

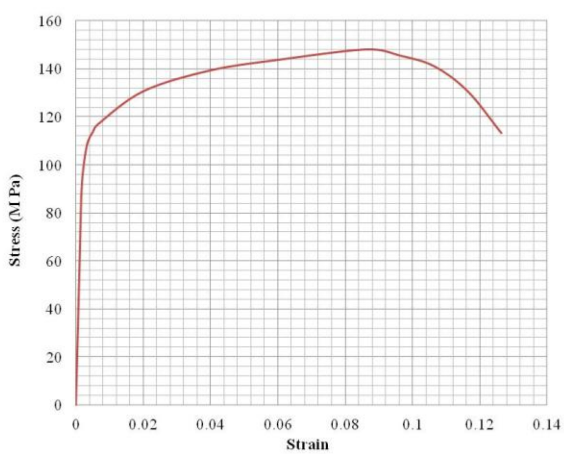


Figure 1: Engineering Stress-Strain curves for Aluminium alloy

The stress-strain curves for XPS and XPE foams were obtained from the compression test. The specimen each of densities 46 kg/m^3 were cut in the form of 50 mm cube and tested under compression. The stress strain curve for the foams is shown in Figure 2. It shows that XPS foam has a considerable elastic region while, XPE has negligible elastic region. However, the plateau regions for XPS and XPE foams are spread till the strain of 0.6-0.75 from where it starts densifying.

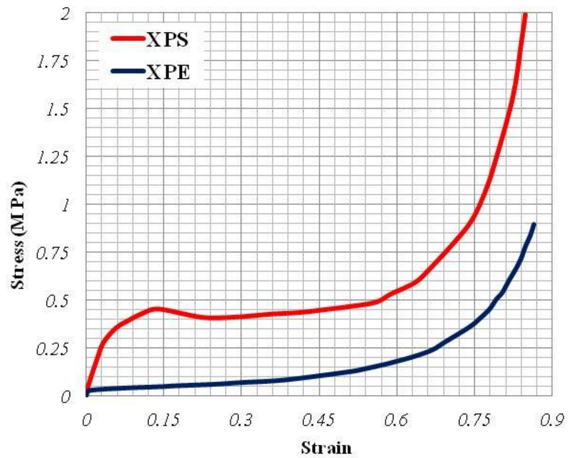


Figure 2: Engineering Stress-Strain curves for XPS and XPE foams

IV. Experiment

Each of the nine test specimen were subjected to load test under compression on a UTM (Model No: TUE-C-1000) of 100 tonne capacity. The test was carried out under Quasi-Static condition with the loading rate of 0.6 kN/s. The experiments were terminated manually when the specimens have crushed to beyond 100 mm from its initial length. The deformation pattern is observed. The load versus displacement curves is plotted and the energy absorbed during the compression process is calculated. The comparison is made between the empty and foam filled tubes.

V. Experimental Results

From the experiments carried out, it was observed that all specimens underwent systematic progressive folding forming 2-3 lobes. This type of crushing mode is known in literature as Diamond mode or non-Axisymmetric sequential folding.

The crushing modes of the empty tubes, XPS foam filled tubes and XPE foam filled tubes are shown respectively in Figure 3, Figure 4 and Figure 5

Figure 3: Crushing modes of the empty tubes

ISSN:2319-6890)(online),2347-5013(print)
01 July 2015

Figure 4: Crushing modes of the XPS foam filled tubes

Figure 5: Crushing modes of the XPE foam filled tubes

The Figure 6 shows the load versus displacement curve. From the plot, it is observed that there is no effect of the foam filling on the peak load.

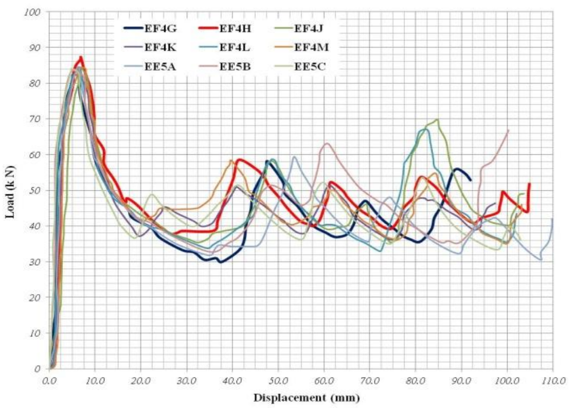


Figure 6: Experimental Load versus displacement curves

The Figure 7 and Figure 8 show the variation with respect to displacement of energy and mean load during the compression process. It shows that there is no significant improvement in energy absorption by foam filling.

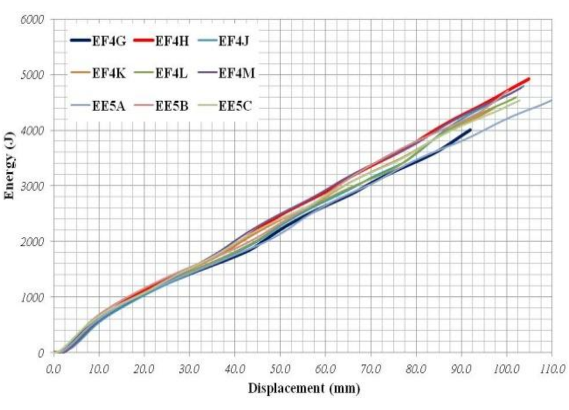


Figure 7: Experimental Energy curves

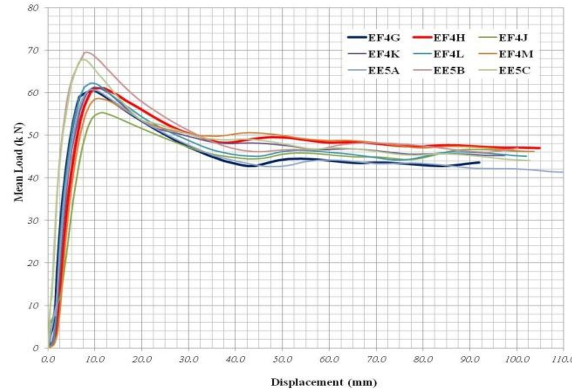


Figure 8: Experimental Mean Load Curves

The details of the crashworthiness parameters are shown in the Table 2

Table 2: Crashworthiness parameters

Expt No.	Pm (kN)	Ea (kJ)	Deformation (mm)	Pmean (k N)	SEA	CFE
EE5A	84.4	4.5	110	41	18.7	49
EE5B	83.2	4.7	100	47	19.5	56
EE5C	84.1	4.5	103	44	18.7	52
EF4G	84.2	4.0	92	44	15.7	52
EF4H	87.3	4.9	105	47	19.1	54
EF4J	84.1	4.8	104	46	18.8	55
EF4K	82.5	4.4	97	45	17.3	55
EF4L	84.4	4.6	102	45	17.9	53
EF4M	84.4	4.8	103	46	18.6	55

VI. FE Modelling

The finite element commercial software LS DYNA R971 is used to study the numerical simulations. The tubes were modelled in Hypermesh using 4-noded shell elements with 2 integration points along the thickness of the tube and are of element size 2 mm. The foams were modelled using Hex element of size 4 mm. Thematerialmodel MAT_PIECEWISE_LINEAR_PLASTICITY (MATL24)was used to model Aluminium tubes and MAT_LOW_DENSITY_FOAM (MATL57) was used to model foam behaviour.

The contact behaviour was modelled using the cards AUTOMATIC_GENERAL and CONTACT_INTERIOR respectively between Tube-Foam interface and self interacting surfaces (internal behaviour of the foam).

The rigid wall was created at bottom of the tube to constrain the motion of the tube along the direction of loading. A prescribed motion defined to a rigid wall created at the top of the tube that crushed the tube quasi-statically. The simulation was terminated after the rigid walled crushed the tube for about 120 mm.

ISSN:2319-6890)(online),2347-5013(print)
01 July 2015

The FE model with Boundary Conditions is shown in the Figure 9

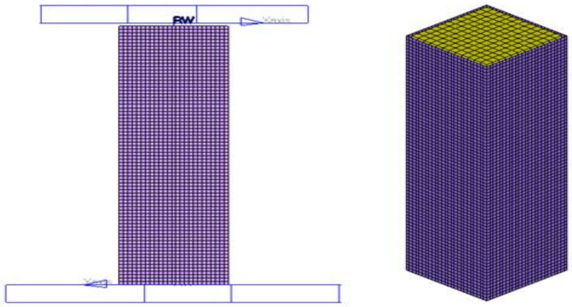


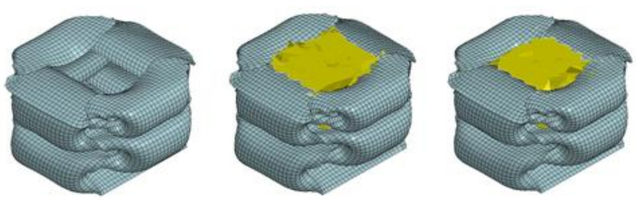
Figure 9: FE model showing the BC

VII. FE Results

Three sets of simulations were performed to simulate the crushing of Empty tube, XPS foam filled tube and XPE foam filled tube. The results were post processed in LS-PrePost 4.0

From the simulations carried out, it was observed that the tubes underwent crushing in the same pattern as was found in the experiments.

The crushing modes of the empty tubes, XPS foam filled tubes and XPE foam filled tubes are shown in Figure 10



A B C

Figure 10: Deformation Pattern

A-Empty; B- XPS filled; C-XPE filled tubes

The Figure 11 shows the Load versus displacement curve during the compression process. From the plot, it is observed that there is no significant effect of the foam filling on curve.

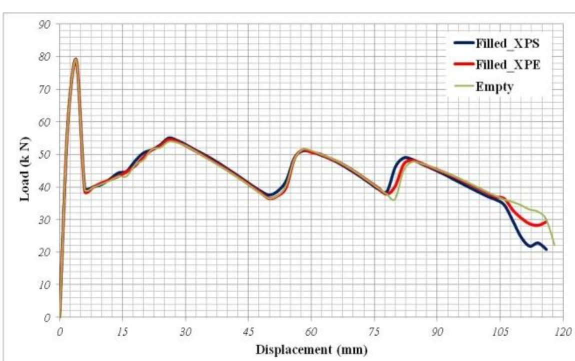


Figure 11: FEM Load versus displacement curve

The Figure 12 and Figure 13 show the variation with respect to displacement of energy and mean load during the compression process. It shows that there is no improvement either in the energy or in the mean load curve by foam filling.

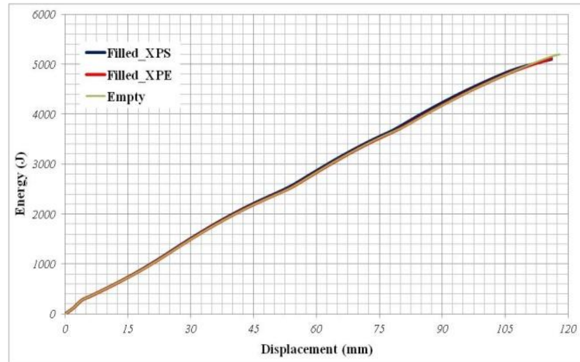


Figure 12: FEM Energy versus displacement curves

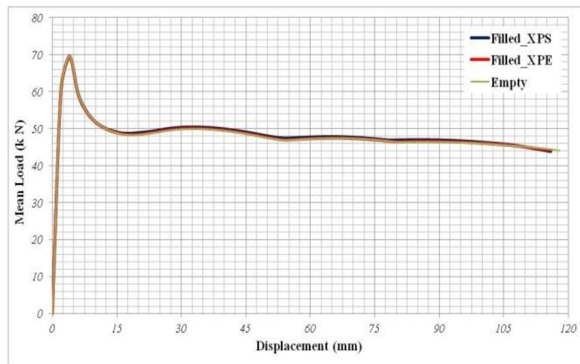


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Figure 13: FEM Mean Load Curves

VIII. Conclusion

The effect of foam filling on the impact characterization (SEA, CFE etc.) of XPS and XPE foam filled aluminium tubes are investigated in this paper. The study shows that the low density foams with lower plateau stress offer less or no resistance to deformation. Hence its participation during energy absorption process is insignificant and therefore it cannot be used in the energy absorption application.

From the present results, it is proposed that a future study can be carried out with the use of higher density foams with higher plateau stress. It is also recommended to make a comparative study between the PU, XPS and XPE foam filled tubes by increasing the densities.

Acknowledgement

The authors remain thankful for the encouragement and support received throughout this research work to Kammavari Sanga group of Institutions, The principal Dr. T. V. Govindaraju and Raghavendra Spectro Metallurgical Laboratories.

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